gold surface, and quantitation of oligonucleotide concentration using fluorescence spectroscopy (as described above).

Removal of all the oligonucleotides from the gold surface and subsequent removal of gold nanoparticles from the solution is critical for obtaining accurate coverage data by fluorescence for several reasons. First, the fluorescence signal of labeled, surface bound DNA is efficiently quenched as a result of fluorescence resonance energy transfer (FRET) to the gold nanoparticle. Indeed, there is almost no measurable signal for fluorescein-modified oligonucleotides (12-32 nucleotide strands, sequences are given above) after they are immobilized on 15.7 ± 1.2 nm gold nanoparticles and residual oligonucleotide in solution is washed away. Second, the gold nanoparticles absorb a significant amount of light between 200 nm and 530 nm, so their presence in solution during fluorescence measurements acts as a filter and diminishes the available excitation energy, as well as the intensity of emitted radiation. The gold surface plasmon band at 520 nm falls at the emission maximum of fluorescein.

Mercaptoethanol (ME) was used to rapidly displace the surface bound oligonucleotides by an exchange reaction. To examine the displacement kinetics, oligonucleotide-modified nanoparticles were exposed to ME (12 mM) for increasing periods of time prior to centrifugation and fluorescence measurements. The intensity of fluorescence associated with the solution free of nanoparticles can be used to determine how much oligonucleotide was released from the nanoparticles. The amount of oligonucleotide freed in exchange with ME increased until about 10 hours of exposure (Figure 29), which is indicative of complete oligonucleotide displacement. The displacement reaction was rapid, which is presumably due to the inability of the oligonucleotide film to block access of the ME to the gold surface (Biebuyck et al., *Langmuir* 9:1766 (1993)).

The average oligonucleotide surface coverage of alkylthiol-modified 12mer oligonucleotide (S12F) on gold nanoparticles was 34 ± 1 pmol/cm$^2$ (average of ten independent measurements of the sample.) For 15.7 ± 1.2 nm diameter particles, this corresponds to roughly 159 thiol-bound 12mer strands per gold particle. Despite slight

particle diameter variation from batch to batch, the area-normalized surface coverages were similar for different nanoparticle preparations.

In order to verify that this method is useful for obtaining accurate oligonucleotide surface coverages, it was used to displace flourophore-labeled oligonucleotides from gold thin films, and the surface coverage data was compared with experiments aimed at getting similar information but with different techniques. In these experiments, gold thin films were subjected to a similar oligonucleotide modification and ME displacement procedure as the citrate stabilized gold nanoparticles (see above). The oligonucleotide displacement versus time curves for the gold thin films are very similar to those measured for gold nanoparticles. This suggests a similar rate of displacement for the thin films, even though the typical surface coverage values measured for these films were somewhat lower than the oligonucleotide coverages on gold nanoparticles. Importantly, the oligonucleotide surface coverages on gold thin films measured by our technique ($18 \pm 3$ pmol/cm$^2$) fall within the range of previously reported coverages on oligonucleotide thin films (10 pmol/cm$^2$ for a 25 base oligonucleotide on gold electrodes determined using electrochemistry or surface plasmon resonance spectroscopy (SPRS) (Steel et al., *Anal. Chem.* **70**:4670-4677 (1998)). Differences in surface coverages are expected due to different oligonucleotide sequences and lengths, as well as film preparation methods.

The extent of hybridization of complementary fluorophore-labeled oligonucleotides (12F') to nanoparticles with surface-bound 12mer oligonucleotides was measured as described above. Briefly, S12F modified nanoparticles were exposed to 12F' at a concentration of 3 μM for 24 hours under hybridization conditions (0.3 M PBS, pH 7) and then rinsed extensively with buffer solution. Again, it was necessary to remove the hybridized strands from the gold before measuring fluorescence. This was accomplished by denaturing the duplex DNA in a high pH solution (NaOH, pH 11) followed by centrifugation. Hybridized 12'F amounted to $1.3 \pm 0.2$ pmol/cm$^2$ (approximately 6 duplexes per 15.7 nm particle; the average number of duplexes per particle was computed by multiplying the normalized hybridized surface coverage in pmol/cm$^2$ by the average particle surface area as

found from size distributions measured by TEM.). In order to measure the extent of non-specific adsorption, S12F modified gold nanoparticles were exposed to fluorophore-labeled non-complementary 12 base oligonucleotides (12F') in 0.3 M PBS. After extensive rinsing (successive centrifugation/redispersion steps) and subsequent high pH treatment, the coverage of non-specifically adsorbed oligonucleotides on the nanoparticles was determined to be on the order of 0.1 pmol/cm$^2$. An analogous procedure was used to measure hybridization to S12F modified gold thin films in order to compare the hybridization results to reported values on gold electrodes. The degree of hybridization, 6 ± 2 pmol/cm$^2$, was consistent with hybridization reported for mixed base 25mer on an gold electrode (2-6 pmol/cm$^2$) (Steel et al., *Anal. Chem.* **70**:4670-4677 (1998)).

Surface coverages and hybridization values of the S12F/12F' system for both nanoparticles and thin films are summarized in Table 7. The most striking result is the low hybridization efficiency (~ 4 % of surface-bound strands on nanoparticles while 33 % of strands on thin films hybridize). Previous studies have shown similarly low hybridization for sufficiently densely packed oligonucleotide monolayers. This may reflect a low accessibility to incoming hybridizing strands, due to a combination of steric crowding of the bases, especially those near the gold surface, as well as electrostatic repulsive interactions.

L. Effect of Oligonucleotide Spacer on Surface Coverage and Hybridization.

Although the high coverage of the S12F oligonucleotide is advantageous in terms of nanoparticle stabilization, the low hybridization efficiency prompted us to devise a means of decreasing steric congestion around the hybridizing sequence. Oligonucleotides (32mer) were synthesized having a 20 dA spacer sequence inserted between the alkylthiol group and the original 12 base recognition sequence. This strategy was chosen based on the assumption that: 1) bases near the nanoparticle surface are sterically inaccessible because of weak interactions between the nitrogenous bases and the gold surface, as well as interstrand steric crowding, and 2) on a 15.7 nm diameter roughly spherical particle, 12mer sequences attached to the end of 20mer spacer units roughly perpendicular to the surface (Levicky et al., *J. Am.*